VI International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2015
B. Schrefler, E. Oñate and M. Papadrakakis (Eds)

AN INTERCOMPONENT HEAT TRANSFER IN A GRAVITATIONAL FLOW MOVEMENTS OF PARTICLES IN AN INCLINED CHUTE

I. N. LOGACHEV*, K. I. LOGACHEV* O. A. AVERKOVA*

* Belgorod State Technological University named after V.G. Shukhov
(BSTU named after V.G. Shukhov), Kostykova str., 46, 308012 Belgorod, Russia
e-mail: kilogachev@mail.ru, web page: http://www.bstu.ru

Key words: Granular Materials, ejection of air, local exhaust ventilation, Applications.

Abstract. To ensure the complete localization of dust emissions, arising from the formation the overpressure in shelters, when heated conveyor overload materials is usually performed through suction of air from two shelters - from the upper (the upper shelter of the drive drum conveyor) and the lower (the lower shelter is place of loading the conveyor.) The main problem when designing of aspiration systems such congestions is to determine the required flow of air, sucked out of the shelters. We have developed a scientifically based method [1,2] which allows us not only to determine the required flow of air, removed from the shelter, but also to choose the rational allocation schemes of aspirating pipes, which is especially important in the cascade arrangement of equipment (feeder -rumble - crusher - conveyor), which covers are linked. The solution of this problem have been achieved in the use of the correct model of dual-velocity continuum "particulate matter - the air", which allowed at a modern level to estimate the dynamic interaction of the flow of air particles under overload of bulk material, as a free running particle jets, and as it moves through a closed overload troughs. The existence of combinations of these regimes is characterized by almost all industrial overload nodes. Intercomponent heat transfer modifies the picture of air movement in these nodes, which we have been examined in the gravitational movement of the particle flux in an inclined chute. The developed procedures of calculation of performance aspiration systems have proliferated in Russia and abroad in the mining and metallurgical industries.

1 INTRODUCTION

The inter-component heat and mass exchange plays a double role. On the one hand, an additional force, thermal pressure caused by buoyant forces, occurs in the chute. On the other hand, the mass exchange results in an additional source or outlet of the gaseous component.

2 INTER-COMPONENT HEAT EXCHANGE IN AN INCLINED CHUTE

Heat exchange, as well as the force interaction between the components, is defined by the flow pattern of the particles and the nature of their movement in the chute. An experimental study of heat exchange was carried out by means of a unit used to examine the inducing properties of an unheated particle flow (Fig. 1).

The value of the heat flow from the particles to air was determined using the enthalpy method:

$$Q = c_2 G_2 (t_к - t_н), \text{ W}, \quad (1)$$

where c_2 is the air heat capacity, J/kg·°; G_2 is the air mass flow rate, kg/s, $t_н$, $t_к$ are air inlet and outlet temperature, at the chute inlet and at its outlet, respectively, °C. The chute walls were heat sealed to prevent the heat exchange with surrounding air.

Research was made on crushed granite (mono fraction of 1.25-2.5 mm) and iron ore (poly fraction with d_{av} – 2.5 mm, the grain composition of which is shown in Table 3.2.) Being heated up to 200-300°C, the material was transferred through a heat-sealed chute with a section of 0.15 x 0.15 m at Θ = 45°, 60°, 75°. As shown by experimental studies, the rate of heat exchange varies with the relative velocity of the particles (Fig. 2a) and with their volume concentration (Fig. 2b), which is consistent with a generalization of heat exchange in dispersed through flows, as performed by Z.R. Gorbis [3]. The established behavior of the inter-component heat exchange for the case of an accelerated fall of particles under consideration was also confirmed by later experiments performed by A.S. Semenov [4] who studied the heat exchange between falling 10.5 mm steel balls and the air in a vertical chute with a section of 0.14 x 0.14 m.

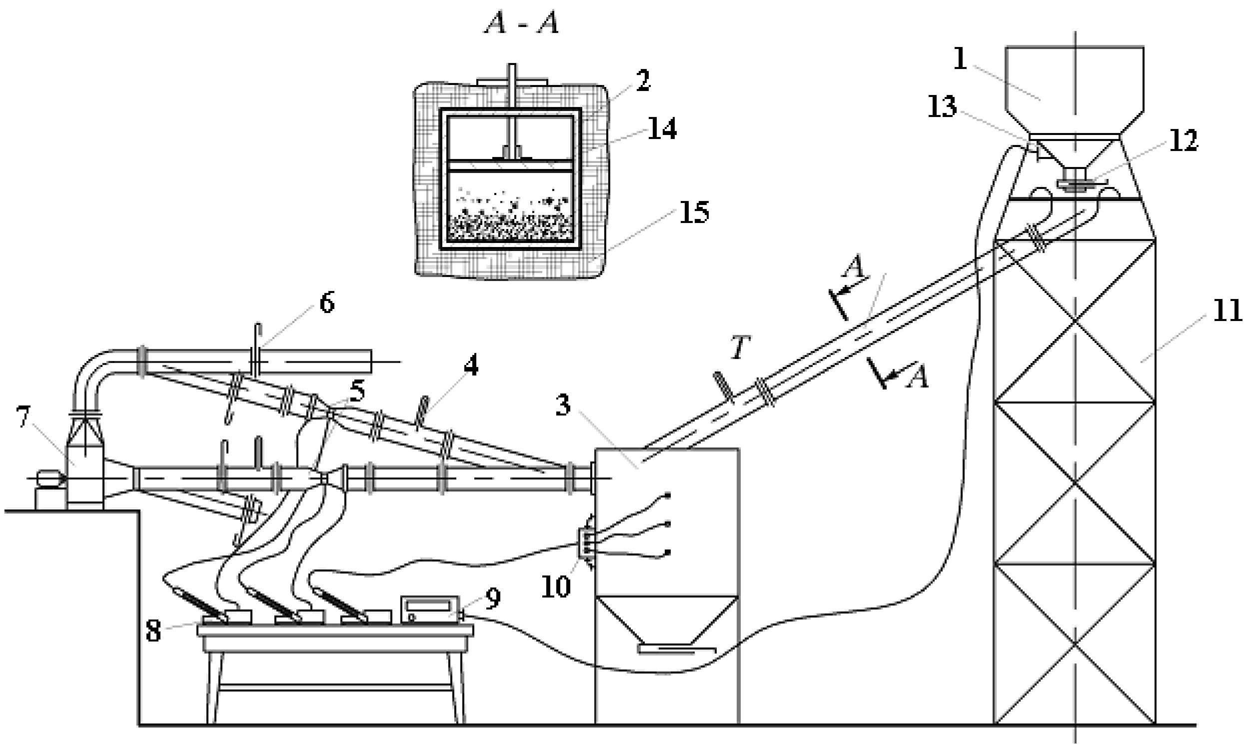

Figure 1: Diagram of the experimental arrangement for the study of injective properties of bulk materials: 1 – upper bin; 2 – chute; 3 – lower bin; 4 – thermometer; 5 – Venturi tube; 6 – damper; 7 – fan; 8 – micropressure gauge; 9 – galvanometer; 10 – blending chamber; 11 – metal frame; 12 – diaphragm; 13 – thermocouple; 14 – chute upper wall; 15 – heat insulation layer

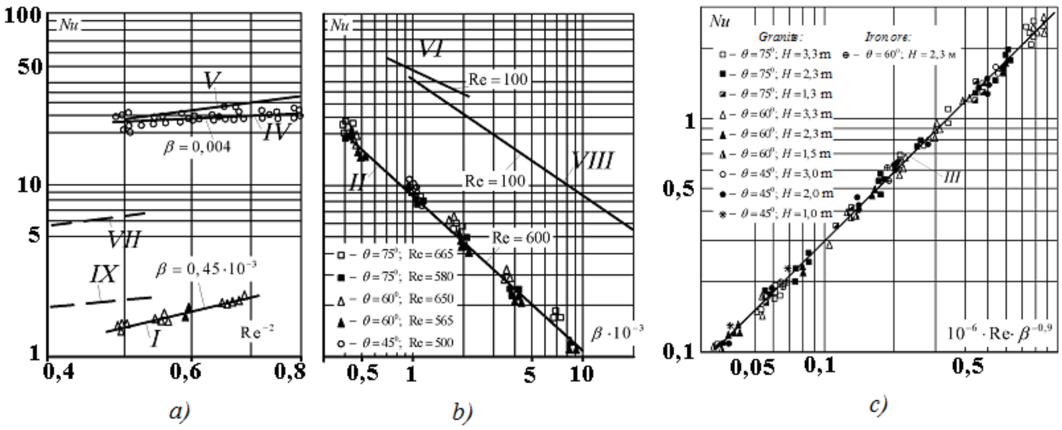

Figure 2: Influence of the number Re and volume concentration on the inter-component heat exchange in the fall of crushed granite particles in an inclined chute (I, II, III) and steel balls in a vertical chute (IV – according to A.S. Semenov), in the flow of free (V, VI – according to Z.R. Gorbis) and stagnant gas suspension (VII, VIII – according to Z.R. Gorbis; IX – according to Yu.N. Morozov)

However, quantitatively, the heat exchange in inclined chutes is significantly different from flows of free gas suspension and heat exchange in a vertical chute. Here, almost every particle participates in heat exchange, and its rate is much higher than in case of particles moving in an inclined chute, where most of them moves near the bottom in constraint conditions. Thus, in our case, we can speak of a conditional (apparent) heat exchange coefficient.

Here, the heat exchange process is analogous to the heat exchange in a mechanically stagnated gas suspension, where there can be seen “dead” zones – areas of a weak interaction with the air – in the flow of particles on the braking elements of mines. This can explain the near values of the Nusselt number (curves I, IX [5, 3]), as well as the coincident behavior of the heat exchange with the increase of the volume concentration (slope angle of lines II and VIII).

As a result of the statistical processing of the experimental data in the range 0.0002 < β <0.01; 400 <Re <700, the following correlation was obtained [6]:

$$Nu = 2{,}95 \cdot 10^{-6}\,\mathrm{Re}\cdot \beta^{-0{,}9}\,, \tag{2}$$

which allows defining the inter-component heat exchange in an inclined chute. Here, the Nusselt and Reynolds numbers are expressed in terms of the average particle diameter and the average relative velocity along the chute length:

$$Nu = \frac{\alpha d}{\lambda_г}\,;\quad \mathrm{Re} = \frac{(v_{1av} - v_2)d}{\nu}\,;\quad v_{1av} = \frac{v_{1н} + v_{1k}}{2}\,,$$

where α is the heat exchange coefficient, W/m^2·°; $\lambda_г$ is the air thermal conductivity, W/m·°.

3 THERMAL HEAD

As a result of the heat exchange, the air density in the chute is different from the density of the surrounding air, and its unit volume is influenced by Archimedes’ buoyant force. Dynamic equation (8) for a prismatic chute is as follows (we suppose $\bar{v}_2 \approx const,\ \ \bar{\beta}_2 \approx 1$)

$$dp = -(\rho_0 - \rho_2) g_x dx - \lambda \frac{dx}{D} \cdot \frac{|v_2| v_2}{2} \rho_2 + dP_Э . \tag{3}$$

Calculate the value

$$P_T = \int_0^l (\rho_0 - \rho_2) g_x dx , \tag{4}$$

usually called the thermal head. Express this value in terms of the chute height and the averaged density of the air

$$P_T = (\rho_0 - \bar{\rho}_2) g H , \tag{5}$$

where

$$\bar{\rho}_2 = \frac{1}{l} \int_0^l \rho_2 dx . \tag{6}$$

Open the symbol of averaging. To this end, express the air density in terms of temperature. Use the thermal expansion coefficient β_T defined by the equation

$$\beta_T = \frac{1}{\rho_2} \left(\frac{\partial \rho_2}{\partial T} \right)_P , \tag{7}$$

to obtain

$$\rho_2 = \rho_0 \exp\left[\beta_T (T_0 - T_2)\right], \tag{8}$$

where T_0, ρ_0 are the temperature (°K) and the density of the surrounding air (kg/m^3); T_2, ρ_2 are the temperature (°K) and density (kg/m^3) of the air in the chute.

To determine the temperature T_2, use heat-transfer equation (92) and the expression for the inter-component heat exchange (95) of Appendix 1. Assuming that the process is stable and ignoring pulse moments, this equation for a one-dimensional problem is as follows

$$d(c_2 \rho_2 T_2 v_2 S_{ж}) = \frac{\beta_1}{V_ч} S_ч \alpha (T_1 - T_2) S_{ж} dx . \tag{9}$$

In addition to the above assumptions, we assume that the temperature of the material is constant along the chute. This assumption is based on the fact that the material is not almost cooled in case of relatively low transfer heights due to a short stay in the chute (about 1 sec). Field measurements (Table 1) showed that the relative cooling does not exceed the accuracy of measurements and varies in the range of 1-3%.

In addition, average the volume concentration of the material, assuming that

$$\beta_1 \approx \beta = \frac{G_1}{\rho_1 S_{ж} v_{1av}} . \tag{10}$$

Integrate equation (9) taking into account accepted simplifications under the condition that $T_2 = T_0$ at the beginning of the chute (at $x = 0$) to obtain

$$T_2 = T_1 - (T_1 - T_0) \exp\left(-\frac{x}{l} W_\alpha \right), \tag{11}$$

where

$$W_\alpha = \beta \frac{S_ч}{V_ч} \alpha S_{ж} l \Big/ (c_2 \rho_2 v_2 S_{ж}) \,. \qquad (12)$$

Then, the expression for the air density in the chute is as follows

$$\rho_2 = \rho_0 \exp\left[-\beta_T (T_1 - T_2) \left(1 - e^{-\frac{x}{l} W_\alpha} \right) \right], \qquad (13)$$

and the averaged density value is

$$\bar{\rho}_2 = \rho_0 \exp\left[\beta_T (T_1 - T_0)\right] \cdot \left\{ Ei\left[\beta_T (T_1 - T_0)\right] - Ei\left[\beta_T (T_1 - T_0) e^{-W_\alpha} \right] \right\} \Big/ W_\alpha \,, \qquad (14)$$

where $Ei(f)$ is an exponential integral function with the argument f.

Insert this result for $\bar{\rho}_2$ into equation (5) to obtain

$$P_T = \left(\rho_0 - \frac{\rho_0 + \rho_{2k}}{2} \varPi \right) g H \,, \qquad (15)$$

where $\varPi$ is a correction coefficient equal to

$$\varPi = 2 e^{-A} \left[Ei(A) - Ei(A e^{-W_\alpha}) \right] \Big/ \left[W_\alpha \cdot (1 + \rho_{2k} / \rho_0) \right], \qquad (16)$$

$$A = (\ln \rho_{2k} / \rho_0) \big/ (1 - e^{-W_\alpha}) \,. \qquad (17)$$

Table 1:Change in the temperature of the material and the vapor-air mixture in the chute in case of transfers of heated wet materials

Transfer group name	Flow of material G_1, kg/s	Drop height H, m	Chute cross-sectional area $S_ж$, m^2	Temperature of material, °C		Temperature of vapor-air mixture, °C		
				$t_{1н}$	t_{1k}	$t_{2н}$	t_{2k}	t_0
Transfer of burnt ore material from the drum cooler to the conveyor belt	10	5.5	0.2	78	77	25	50	7
Transfer of burnt ore material from a conveyor to a conveyor	200	6.0	0.4	65	63	20	45	12
Transfer of burnt ore material from a conveyor through an intermediate bin to another conveyor	200	12.0	0.4	62	60	20	40	10
Transfer of iron ore pellets from the drum cooler to a conveyor	8	3.0	0.2	73	70	30	35	6
Transfer of iron ore pellets from a conveyor to another conveyor	30	3.5	0.8	70	68	30	50	10

In the area $w_\alpha < 1$; $0.6 < \rho_{2k}/\rho_0 < 1$, the coefficient Π is almost equal to 1, and the value of the averaged air density in the chute is equal to the arithmetic mean value [7]. In the general case, the thermal head equals

$$P_T = \left(\rho_0 - \frac{\rho_{2н} + \rho_{2k}}{2}\right) gH \ . \tag{18}$$

Here, ρ_{2k} is the air density at the end of the chute at T_{2k} calculated taking into account the correlation obtained for the inter-component heat exchange (2) according to

$$T_{2k} = T_1 - (T_1 - T_{2н}) e^{-W_\alpha} \ . \tag{19}$$

4 AIR VELOCITY IN THE CHUTE

Integrate dynamic equation (3) to obtain

$$P_к - P_н = -P_T - \lambda \frac{l}{D} \frac{|v_2| v_2}{2} \rho_2 + P_э \tag{20}$$

or, expressing the pressure at the beginning and end of the chute in terms of the coefficients of local resistances

$$P_к = P_0 + \zeta_k \frac{|v_2| v_2}{2} \rho_2 \ , \ P_н = P_0 - \zeta_н \frac{|v_2| v_2}{2} \rho_2 \ , \tag{21}$$

equation (20) is as follows

$$\sum \zeta \frac{|v_2| v_2}{2} \rho_2 = P_Э - P_T \ . \tag{22}$$

Which shows that the difference between the induction head and thermal one determines the air flow and the direction of air flow in the chute, when transferring heated material. Three cases are possible in this regard.

Case 1: $P_Э > P_T$. The air moves downwards (forward flow). The value of the thermal head acts as an additional resistance. The volume of induced air is defined by an obvious equality:

$$Q_Э = \sqrt{(P_Э - P_T)/R_{ж}} \ . \tag{23}$$

Case 2: $P_Э < P_T$. Air moves toward the falling material (counter flow) under the prevailing thermal head. The induction head only slows the movement:

$$Q_{ж} = \sqrt{(P_T - P_Э)/R_{ж}} \ . \tag{24}$$

However, it should be borne in mind that the sum of the coefficients of local resistances will not generally be equal to the similar amount in case of the forward flow.

Case 3: $P_Э = P_T$. There is no direction of air movement in the chute. Only local aerodynamically unstable air circulations can occur in this case. Consider in detail the condition of the aerodynamic instability. Designate the temperature in the chute as T_{2cp} (note that in the limiting case $T_{2cp} \to T_1$). The air density is according to (8)

$$\rho_2 = \rho_0 \exp\left(\beta_T (T_0 - T_{2cp})\right) \tag{25}$$

or, considering that in most practical cases $(T_2 - T_0)\,\beta_T$ <<1,

$$\rho_2 = \rho_0\left[1-(T_{2cp} - T_0)\beta_T\right]. \tag{26}$$

The value of the thermal head in this case is

$$P_T = gH\rho_0(T_{2av} - T_0)\beta_T. \tag{27}$$

The value of the induction head

$$P_Э = \kappa_m \psi^* \frac{\rho_2}{\rho_1} G_1 (v_{1k}^3 - v_{1H}^3)/(6a_T S_{ж}). \tag{28}$$

Then, the condition of equality of these heads takes the form of the following criterial equation

$$(1-n^3)\cdot \mathrm{Re}_k^2/(6Eu_0^*) = Gr, \tag{29}$$

where Gr is Grashof number, which characterizes the ascensional forces and equals

$$Gr = \beta_T \frac{gH^3}{\nu^2}(T_{2av} - T_0), \tag{30}$$

Re_k is Reynolds number, which characterizes the kinetic capacity of the particle flow at the end of the chute and equals

$$\mathrm{Re}_k = v_{1k} H/\nu, \tag{31}$$

Eu_0^* – is the modified Euler criterion which characterizes the aerodynamic drag strength of the particles and equals

$$\mathrm{Eu}_0^* = S_{ж} \frac{C_y^2}{2}\rho_0 \Big/ (G_1 v_{1k}). \tag{32}$$

The balance of the forces described by criterial equation (29) has been confirmed during an experiment involving the transfer of heated crushed granite (Fig. 3).

Thus, the amount of air being moved along the chute (with the local suction units operating) is, in the general case, equal to

$$Q_ж = \frac{P_Э - P_T + P_2 - P_1}{\sqrt{\left|P_Э - P_T + P_2 - P_1\right|/R_ж}}, \tag{2}$$

where P_1, P_2 are rarefactions kept up with the local suction units in the upper hood and the lower one (adjacent to the upper and lower ends of the chute, respectively), Pa.

Or in a dimensionless form

$$\varphi_k\left|\varphi_k\right| = Bu\cdot\left[\left|1-\varphi_k\right|^3 - \left|n-\varphi_k\right|^3\right]\Big/3 - Eu_T, \tag{34}$$

where

$$Eu_T = (P_T - P_2 + P_1)\Big/\left(\sum\zeta\frac{v_{1k}^2}{2}\rho_2\right). \tag{35}$$

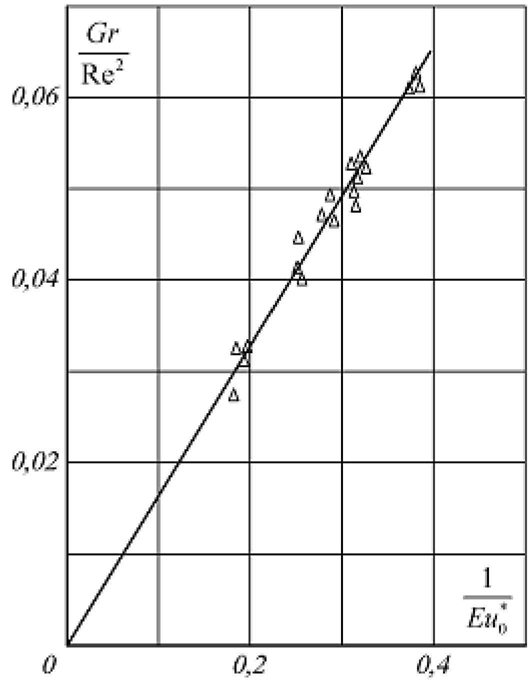

Figure: 3. The balance of the forces of induction and thermal pressures in the chute when transferring heated granite (d_{av}= 1.88 mm, $n \approx 0$)

The minus symbol before the value φ_k (or $Q_{ж}$) denotes a case of a counter flow, the case of balance occurs with

$$(1-n^3)Bu = 3Eu_T\,. \tag{36}$$

4 INFLUENCE OF MASS EXCHANGE ON THE VOLUMES OF INDUCED AIR

Consider the movement of the heated wet material accompanied with moisture evaporation from the surface of falling particles. Equations of mass exchange for a one-dimensional problem will be as follows

$$\frac{d}{dx}\beta_1\rho_1 v_1 S_{ж} = -J\cdot S_{ж}\,;\;\frac{d}{dx}\beta_2\rho_2 v_2 S_{ж} = J\cdot S_{ж}\,, \tag{37}$$

where J is the volumetric evaporation rate, kg/(s·m^3). Respectively, for an impulse

$$\frac{d}{dx}\beta_1\rho_1 v_1 v_1 S_{ж} = S_{ж}\beta_1 a_T\rho_1 - S_{ж}\beta_1\kappa_m\psi^*\frac{|v_1-v_2|(v_1-v_2)}{2}\rho_2 - Jv_1 S_{ж}\,, \tag{38}$$

$$\frac{d}{dx}\beta_2\rho_2 v_2 v_2 S_{ж} = S_{ж}\beta_2 g_x(\rho_2-\rho_0) + S_{ж}\beta_1\kappa_m\psi^*\frac{|v_1-v_2|(v_1-v_2)}{2}\rho_2 - \frac{d}{dx}\beta_2 P_2 S_{ж} - \lambda\frac{S_{ж}\beta_2}{D}\frac{v_2^2}{2}\rho_2 + Jv_1 S_{ж}. \tag{39}$$

Assuming still that the volume concentration of the material is small ($\beta_1 << 1$; $\beta_2 \approx 1$), the last correlation with (36) can be written as ($S_{ж}$ - const):

$$\frac{dp}{dx} = g_x(\rho_2 - \rho_0) + \beta_1 \kappa_m \psi^* \frac{|v_1 - v_2|(v_1 - v_2)}{2} \rho_2 - \frac{\lambda}{D} \frac{v_2^2}{2} \rho_2 + J(v_1 - v_2)\,. \qquad (40)$$

Express the mass transport equation of the gaseous component in terms of the moisture content (m) and the flow rate of dry air ($G_в$)

$$J = \frac{G_в}{S_{ж}} \frac{dm}{dx}\,, \qquad (41)$$

and write obvious equations of flow

$$\rho_2 v_2 S_{ж} = G_в (1 + m) \qquad (42)$$

and the averaged values of the velocities of the components

$$\overline{v}_1 = \frac{1}{l} \int_0^l v_1 dx = v_{1k} \cdot \frac{2}{3} \cdot \frac{1 - n^3}{1 - n^2}\,, \qquad (43)$$

$$\overline{v}_2 = \frac{1}{l} \int_0^l v_2 dx \approx G_в (1 + m_{ср}) / (\overline{\rho}_2 S_{ж})\,. \qquad (44)$$

Assuming that the densities and velocities of the components on the right side of equation (40) are averaged, after integration on the condition that

$$P(0) = -P_1 - \zeta_н \frac{v_{2н}^2}{2} \rho_{2н}\,;\ P(l) = -P_2 + \zeta_k \frac{v_{2k}^2}{2} \rho_{2k} \qquad (45)$$

the following equation is obtained

$$\sum \zeta^* \frac{\overline{v}_2^2}{2} \rho_2 = -P_T + P_Э + P_2 - P_1 + P_J\,, \qquad (46)$$

where P_J is the pressure force that occurs due to moisture evaporation from the falling particles (for brevity, we call this value the interphase pressure), which is equal to

$$P_J = \int_0^l J(v_1 - v_2) dx \approx G_1 (m_k - m_н)(\overline{v}_1 - \overline{v}_2) / S_ж\,, \qquad (47)$$

$\Sigma\zeta^*$ is the sum of the coefficients of local resistance which is equal to

$$\sum \zeta^* = \zeta_н \left(\frac{1 + m_н}{1 + m_{ср}} \right)^2 \frac{\overline{\rho}_2}{\rho_{2н}} + \zeta_k \left(\frac{1 + m_к}{1 + m_{ср}} \right)^2 \frac{\overline{\rho}_2}{\rho_{2k}} + \lambda \frac{l}{D}\,. \qquad (48)$$

In the dimensionless form, the equation can be as:

$$\overline{\varphi}^2 = Bu \left[|1 - \overline{\varphi}|^3 - |n - \overline{\varphi}|^3 \right] \Big/ 3 - Eu_T + Eu_J \left(\frac{2}{3} \frac{1 - n^3}{1 - n^2} - \overline{\varphi} \right), \qquad (49)$$

where $Bu = \dfrac{\psi^* \kappa_m G_1 v_{1k}}{a_T S_{ж} \rho_1 \sum \zeta}$, Eu_T are numbers defined by correlation (35), and at $\Sigma\zeta \rightarrow \Sigma\zeta'$ and $\rho_2 \rightarrow \overline{\rho}_2$

$$Eu_J = G_в (m_k - m_н) \cdot v_{1k} \Big/ \left(S_ж \sum \zeta^* \frac{v_{1k}^2}{2} \bar{\rho}_2 \right). \tag{50}$$

From this, the mass flow rate of non-condensing (dry) part of the air can be obtained

$$G_в = \bar{\varphi} \cdot v_{1k} S_ж \frac{\bar{\rho}_2}{1 + m_{av}} . \tag{51}$$

Then, the amount of vapor-air mixture transferring from the chute to the lower cavity (hood) can be obtained based on the obvious equality

$$G_{2k} = G_в (1 + m_k) = \bar{\varphi} v_{1k} S_ж \bar{\rho}_2 \frac{1 + m_k}{1 + m_{av}} . \tag{52}$$

Thus, the amount of induced air during transfers of wet materials is increased not only due to the water vapors resulted from evaporation, but also due to additional forces of the interphase pressure.

12 CONCLUSIONS

It was established that due to non-uniformity of particles distribution the intensity of intercomponent heat exchange in a chute is by an order lower than the intensity of heat exchange in a vertical channel with a uniform distribution of particles. Counteracting forces resulting from the heat exchange of buoyancy forces contribute to a decrease in suction properties of a bulk material stream. The direction and value of the air velocity in a chute at transfer of a heated material is determined by the relation between heat and induction pressures. When transferring wet heated materials, the amount of air induced is increased due to water vapors resulting from condensation and auxiliary interphase pressure forces.

The reported study was partly supported by RFBR, research projects No. 14-41-08005r_ofi_m and 14-08-31069-mol_a

REFERENCES

[1] Logachev, I.N. and Logachev, K.I. Industrial Air *Quality And Ventilation: Controlling Dust Emissions*. CRC Press, (2014).
[2] Neykov, O.D. and Logachev, I.N. *Aspiration in the production of powder materials*. Moscow: Metallurgy (1973).
[3] Gorbis, Z.R. *Heat exchange and hydromechanics of dispersed through flows. 2nd revised and enlarged edition*. M: Energiya, (1970).
[4] Semenov, A. *Study of ventilation in chuting of hot materials. Abstract Thesis ... Cand.Sc. (Engineering).* Sverdlovsk, (1975).
[5] Morozov, Yu.I. *Study of heat exchangers with a falling layer: Thesis ... Cand.Sc. (Engineering).* Kiev, (1967).
[6] Logachev, I.N. Intercomponent heat exchange in a stream of a bulk material in closed

chute transfers. *Proceedings of the 4th Republic Interuniversity Conference for Evaporation, Combustion and Gas Dynamics of Dispersion Systems*. Odessa: OGU, (1969).

[7] Logachev, I.N. Thermal head in hot material transfers. *Air ventilation and treatment*. Moscow: Nedra (1970) **4**: 120-124.

Legend

a_t – acceleration of a stream of particles in a chute, m/s;
c – airborne speed of particles, m/s;
c_y – conventional airborne speed, m/s;
c_1 – heat capacity of material particles, J/(kg·K);
c_2 – air heat capacity (with ρ = const), J/(kg·K);
D – hydraulic diameter of a chute (channel), m;
d, $d_э$ – particle diameter (sphere diameter equivalent to a particle in terms of volume), m;
E – specific energy, J/kg;
G – mass flow (G_1 – particles, G_2 – air, $G_в$ – dry air), kg/s;
g – gravity factor (g_x – chute x-direction gravity factor), m/s^2;
H – drop height of particles, m;
$h = x = x/l_\infty$ – dimensionless drop height of particles;
I – intensity of interphase transformations, kg/(s·m^2);
k – particle drag coefficient ($k_г$, k_f, k_s – geometric, $k_д$ – dynamic);
k_m – particle frontal area/volume ratio, 1/м;
$L_э$, $Q_{э,к}$ – induced air flow in a chute, m^3/s;
l – chute length, m;
M – mass force (M_1 – particles, M_2 – air), N/kg
n – relation of the initial particle speed in a chute to the particle speed in the chute channel;
P – pressure ($P_э$ – chute injection pressure, $P_т$ – chute thermal pressure, P_a, P_0 – outside chute,
P_j – chute interphase pressure), Pa;
$P_ч$ – particle weight, N;
$Q_{ж}$ – chute air flow, m^3/s;
Q_{21} – air-to-particles heat exchange rate, W/m^3;
q – heat flow, W/m^2;
R – aerodynamic drag of bombarding particles, N;
$P_п$ – aerodynamic force of stream particle, N;
R, R_0 – aerodynamic force of single particle, N;
$R_{ж}$ – chute hydraulic characteristic, kg/m^3;
S – area of particles flow section, m^2;
S, $S_{ж}$ – cross sectional area of a chute (channel), m^2;
s – surface ($s_м$, s_4 – particles, $s_ш$ – sphere), m^2;
T – temperature, °K;
T_{2av} – mean air temperature in a chute, °K;

T_0 – average air temperature outside a chute, °K;
t, τ – time (τ_∞ – relaxation time), s;
V – volume ($V_ч$ – particle volume), m^3;
υ, v, ϑ – velocity (υ, υ_1 – particles; $\upsilon_{1к}$, $\upsilon_к$ – particles at the chute outlet; υ_{10}, $\upsilon_{1н}$ – particles at the chute inlet; υ_2, u – air), m/s;
$u_{вх}$ – exhaust pipe entry section air velocity, m/s;
$w = \upsilon - u$ – relative particle velocity, m/s;
w – material humidity, %;
x – path of particles over a chute, m;
α – interelement exchange ratio (α_m – mass, kg/(s·m^2·K); α_T, α – heat, W/(m^2·K);
β – volume concentration (β_1 – particles, β_2 – air), m^3/m^3;
$\beta_т$ – air thermal expansion coefficient, 1/°K;
ζ – local drag factor (LDF);
λ – hydraulic resistance coefficient;
$\lambda_г$ – air thermal conductivity, W/(m·K);
ν – air kinematic viscosity coefficient, m^2/s;
$\vec{\Pi}$ – surface force vector, N/m^2;
Π_c – material particle constraint ratio, w/o unit of measurement;
$\Pi_д$ – dynamical interference activity factor, w/o unit of measurement;
ρ – density (ρ_1, ρ_m – particle material; ρ_2, ρ – particle stream air; ρ_0 – air outside a chute; ($\rho_{2н}$, $\rho_{2к}$ – air at the chute inlet and outlet), kg/m^3;
τ – time, s;
ψ – particle resistance coefficient (ψ_0 – particles in the area of self-similarity, $\psi_{0ш}$ – sphere in the area of self-similarity, ψ_c – airborne particles, ψ * – stream particles), w/o unit of measurement.

Criteria:
$Re = wd\rho/\eta$ – Reynolds number;
$Bu = \psi^* k_m G_1 \upsilon_{1k} / \left(\sum \zeta a_T S_{ж} \rho_1\right)$ – Butakov number;
$Eu = S_ж \dfrac{c_y}{2} \rho_0 / (G_1 v_{1k})$, $Eu^* = \Delta p / \left(0,5 \sum \zeta \upsilon_{1k}^2 \rho_2\right)$ – Euler number;
$Gr = \beta_т \dfrac{gH^3}{\nu^2} (T_{2av} - T_0)$ – Grashof number;
$Nu = \alpha d / \lambda_г$ – Nusselt number.